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Influence of Fuel Sulfur on Fuel Nitrogen Oxidation Mechanisms

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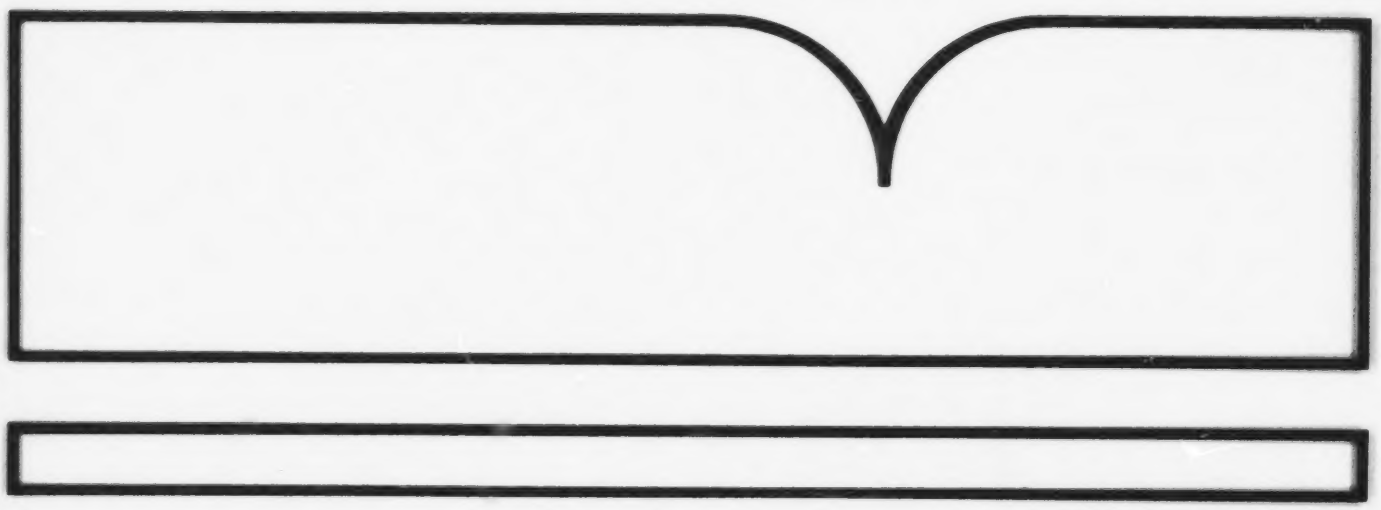

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16. ABSTRACT The paper discusses laboratory premixed flat flame studies showing that, under fuel rich conditions, fuel sulfur can have a radical influence on fuel NO formation mechanisms. Both enhancements and apparent inhibition of fuel NO were observed, depending on the equivalence ratio and the residence time at which the measurement was made. The effect of sulfur on "prompt" NO was similar. This first order effect was shown to manifest itself in a significant increase in NOx emissions when a fuel containing chemically bound nitrogen is burned with sulfur in an axial (low swirl) turbulent diffusion flame. Under these conditions, in which local hot fuel environments dominate, fuel oils containing both nitrogen and sulfur are likely to give higher NO emissions than those containing little sulfur. Likewise, prompt NO mechanisms can be significant for Thermal NO, and enhancement thereof by SO2 in the fuel can greatly influence resultant Thermal NO emissions.

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INFLUENCE OF FUEL SULFUR ON FUEL NITROGEN OXIDATION MECHANISMS

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Laboratory premixed flat flame studies showed that under fuel rich conditions, the presence of fuel sulfur could have a radical influence on fuel NO formation mechanisms. Both enhancement and apparent inhibition of fuel NO were observed, depending on the equivalence ratio, and the residence time at which the measurement was made. The effect of sulfur on "prompt" NO was similar.

This first order effect was shown to manifest itself in a significant increase in NO_x emissions when a fuel containing chemically bound nitrogen is burned with sulfur, in an axial (low swirl) turbulent diffusion flame. Under these conditions, in which local hot fuel environments dominate, fuel oils containing both nitrogen and sulfur are likely to give higher NO emissions than those containing little sulfur. Likewise, "prompt" NO mechanisms can be significant for Thermal NO, and enhancement thereof by SO_x in the fuel can greatly influence resultant Thermal NO emissions.

Introduction

Chemically bound nitrogen in fossil fuel has been shown to be an important contributor to nitrogen oxide emissions from combustion processes. Recent research[1-3] has focussed on mechanisms governing the oxidation of fuel nitrogen to fuel NO in the hope that the insight and understanding gained, thereby, will lead to development of new combustion modifications for NO_x control. However, many fuels containing chemically bound nitrogen also contain sulfur, in various amounts. The question can, therefore, be posed whether the sulfur content of a fuel is likely to have a major influence on the resulting NO_x emissions and specifically whether the presence of fuel sulfur will cause major changes in mechanisms of fuel NO formation. Furthermore, since there exists a wide variety of possible combustion conditions and combustion modifications, it is to be expected that the potential importance of SO_x/NO_x interactions depends not only on the fuel quality, but also on the conditions under which the fuel is burned.

This project was divided into two phases. Phase I consisted of an investigation of Fuel NO_x/SO_x mechanisms in a premixed laminar flame environment, primarily under fuel rich conditions. The effects on Fenimore "prompt" NO were also investigated, because of similarities between this and Fuel NO. Phase II consisted of exhaust NO measurements from those turbulent diffusion flames judged to promote local environments found in Phase I to be conducive to large Fuel NO/Fuel S interactions. This work therefore also provides some insight into the relationship between kinetic phenomena in a premixed flat flame environment and those that are important in certain turbulent diffusion flame environments.

Phase I: Premixed Flat Flames

Previous work by Wendt and Ekmann[4] showed that addition of high levels of SO_2 or H_2S to premixed, flat, methane air flames could inhibit thermal NO formation significantly. De Soete,[5] however, found that low levels of fuel sulfur could enhance both "prompt NO" formation and fuel NO in hot rich hydrocarbon flames. This work addresses the questions: to what extent does the presence of fuel sulfur radically alter fuel nitrogen oxidation mechanisms, and when is this likely to be important under practical combustion configurations?

Experimental Burner

The premixed flat flame burner was similar to that utilized by others.[6] It was nominally 5 cm I.D.

and allowed a flat flame to be stabilized over a coarse stainless steel screen (10 × 10 mesh, 0.028" wire). The burner was enclosed by a 15 cm I.D., 60 cm high quartz chimney, the inside surfaces of which were purged with nitrogen in order to prevent soot deposition.

The quartz chimney was enclosed at the top by a firebrick which allowed the nitrogen purge and much of the exhaust flow to exit through 10, 6 mm dia. holes, situated near the quartz wall, and the remaining exhaust flow, including the center streamline to exit through a 2.5 cm dia. minichimney. This configuration allowed data far from the flame front to be taken without dilution from the purge or surrounding air.

Temperature measurements were made using the sodium D-line reversal technique, with experimentally obtained corrections for the glass chimney surfaces. Flows of major (O_2, CH_4, Ar) and minor species (C_2N_2, SO_2, H_2S) were controlled and metered with sonic orifices, rotameters and laminar flow elements where appropriate.

Sampling was accomplished through both uncooled and cooled quartz probes. NO_x analysis was by chemiluminescence and a Molybdenum converter. Teflon lines were used throughout. We were concerned about reactions occurring at room temperature in the sampling line. Special experiments, including some in which SO_2 in the sample line was removed at various points, showed that our NO measurements were not due to an interference between sulfur and any potential NO_x forming species between the probe and the analyzer. Both the hot and cooled probes withdrew the sample through a 1.5 mm orifice, allowing a normal sampling rate of 1.3 liters/min. Special tests on the hot quartz probe showed that when soot, previously exposed to SO_2, was present, the baseline (no sulfur) NO was lowered by 7 ppm, compared to results from the cooled probe. The cooled probe did not allow the build up of soot, and changing sampling rates by a factor of five did not change "exhaust" ppm NO measured, both in the presence and absence of sulfur. The cooled probe, however, caused the peak flame temperature of 1953°K to drop 30°K when it was in the immediate vicinity of the point where temperature was measured. This interference became negligible 2 cm away from the probe. Most of the results reported below are with the cooled probe, except as noted. A chart recorder was used to observe transients and baseline reproducibility. Changing or cleaning the porous disk and screen on the burner had no effect on results.

Results

Figs. 1 through 3 show the effects of various fuel sulfur levels on fuel NO profiles at various stoichiometries. The total dry and wet molar flow rates of the burner gas, used to calculate nominal residence times and fuel nitrogen conversion, were those based on chemical equilibrium in the fuel rich mixtures. In general, the sulfur additive ranged from 0.2 through 3.8 mole percent of the fuel; the nitrogen contents were 0.2 and 1.0 mole precent nitrogen in the fuel. Specific details for each condition investigated can be found in the figures and figure captions. The major species were argon, methane and oxygen. In all cases, there was no evidence of NO_2, either with or without sulfur present.

At a stoichiometric ratio of 0.46 ($\Phi = 2.17$) sulfur in greater than 0.2 mole percent in fuel had a large qualitative and quantitative effect on the entire fuel NO profile (Fig. 1). Open symbols denote data taken with the cooled probe, shaded symbols are those taken with the hot probe. The baseline fuel NO rose quickly to a constant 10 ppm. Addition of 3.8 mole percent sulfur dioxide to the fuel prompted

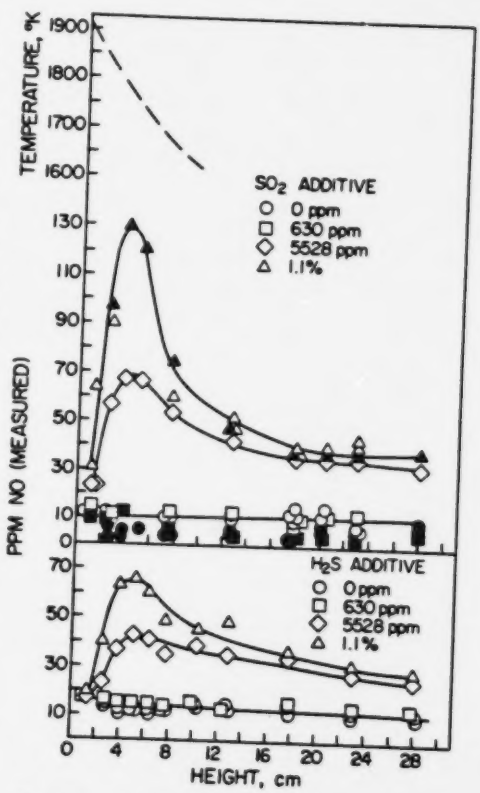


FIG 1. Laminar Premixed Flame: $\Phi = 2.17$ (CH_4 = 6.08 l/min; O_2 = 5.62 l/min, Ar = 8.92 l/min, C_2N_2 = 6.3 ml/min. 100% conversion of C_2N_2 = 553 ppm, 1 cm = 7.67 ms at 1900°K)

a rapid increase of fuel NO with a peak of 130 ppm occurring downstream of the luminous zone of the flame. This high value decayed slowly to 40 ppm over a residence time greater than 0.1 seconds. Although sulfur does act as a combustion inhibitor, the position of the luminous zone of the flame varied only slightly within a few millimeters of the grid. However, it is important to note that with sulfur present, NO is destroyed by a slow reaction at low temperatures (less than 1600°K). This does not occur in the absence of sulfur. The lower portion of Fig 1. shows results of H_2S addition, in similar quantities as the SO_2 in the upper portion. Qualitatively similar profiles were obtained as with SO_2, but comparison with an upper portion indicates a less extreme effect. It should be noted that H_2S addition does lower the stoichiometric ratio, thus, tending to lower fuel nitrogen conversions. These data are in contrast to De Soete's[8] results which showed H_2S to have a larger effect on ammonia conversion than did SO_2. However, our results indicate that it is sulfur, rather than the initial form of sulfur, which is responsible for the large effect observed. Furthermore, the fact that the baseline NO does not change over a distance of 28 cm indicates that, along the centerline, dilution from external gases is not significant. Although not observed, any recirculation of exhaust gases would serve to lower peak NO values. Therefore, the effect of sulfur on Fuel NO is at least as great as, and possibly greater than that shown in Fig. 1.

Fig 2. shows profiles at $\Phi = 1.64$ and $\Phi = 1.47$. Again, sulfur added to the fuel radically changed fuel NO mechanisms. The peak now occurred closer to the luminous zone in the flame, and a steady NO consumption brings the NO profile below the baseline case. In this case, whether fuel sulfur inhibits or enhances NO depends entirely on where

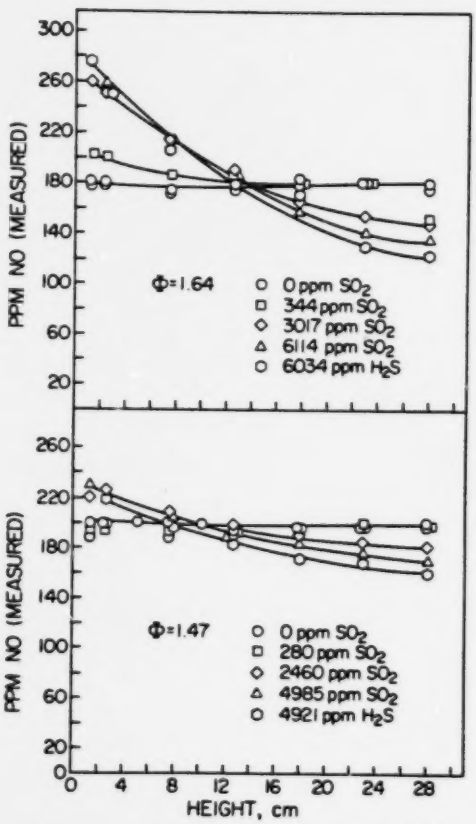


FIG 2: Laminar Premixed Flame: $\Phi = 1.64$ (CH_4 = 6.08 1/min, O_2 = 7.4 1/min, Ar = 24.3 1/min, C_2N_2 = 6.3 ml/min. 100% conversion = 357 ppm, 1 cm = 4.47 ms at 2100°K) and $\Phi = 1.47$ (CH_4 = 6.08 1/min; O_2 = 8.25 1/min; Ar = 32.0 1/min, C_2N_2 = 6.3 ml/min. 100% conversion = 300 ppm, 1 cm = 4.00 ms at 1980°K)

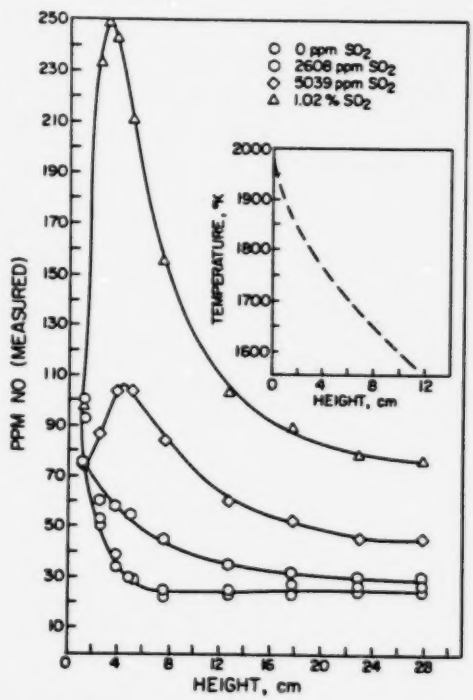


FIG 3. Laminar Premixed Flame: $\Phi = 2.17$, 1.05% fuel N (CH_4 = 6.08 1/min, O_2 = 5.62 1/min, Ar = 10.92 1/min, C_2N_2 = 31.8 ml/min. 100% conversion = 2793 ppm, 1 cm = 7.40 ms at 1970°K).

the measurement is taken. Peak temperatures in Fig. 2 were significantly higher than those at the richer case. For $\Phi = 1.64$ the temperature decayed from 2100°K to 1800°K within 12 cm. For $\Phi = 1.47$ the decay was from 2000°K to 1800°K within 16 cm.

Results for a fuel nitrogen content of 1 mole percent and a stoichiometric ratio of 0.46, are shown in Fig. 3. At the higher nitrogen content, a significant reduction in baseline NO, without sulfur, was observed close to the flame front. With sulfur, the NO profile again formed a high peak followed by a slow decay. Decay of NO again occurred at temperatures below 1600°K when sulfur was present, although not when sulfur was absent.

Fig 4. shows the effect of fuel sulfur addition on NO from N_2 fixation at $\Phi = 1.59$ (Fenimore prompt NO),[7] at two different flame temperatures. The data lead to the following conclusions: 1) Low levels of sulfur enhance prompt NO, and this effect is greater at higher temperatures; 2) counteracting this, sulfur can also inhibit NO (in agreement with previous data.[4]) Therefore, there exists a sulfur level at which maximum enhancement occurs and this level depends on temperature. At 2200°K a sulfur level of 2539 ppm caused a maximum enhancement while at 2075°K, this occurred at 580 ppm SO_2. Extrapolation to lower temperatures leads to the prediction that there sulfur would have no net enhancement effect, although it may inhibit "prompt" NO.

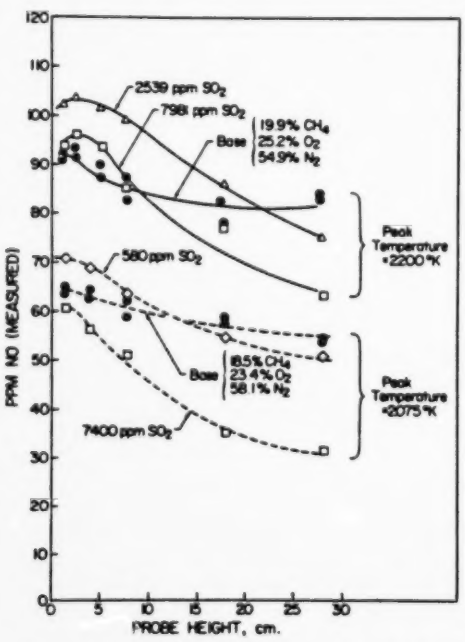


FIG 4. Laminar Premixed Flame: N_2 Fixation-Prompt NO: $\Phi = 1.59$.

Phase II: Turbulent Diffusion Flames

The premixed data indicated greatest effects of fuel sulfur on fuel NO_x under substoichiometric conditions. Therefore, in determining whether those effects pertain to turbulent diffusion flames, primary emphasis was on those flame types in which fuel rich pockets are likely to occur. All data reported below, however, are for overall excess air conditions.

Experimental Combustor

Swirling turbulent diffusion flames were supported on a small scale 25 kw burner in a 15 cm I.D. diameter combustor. Hardware details can be found elsewhere.[8,9] It is important to note that by proper adjustment of fuel and air velocities, of volume fraction of secondary air given tangential momentum (hereafter denoted by % swirl), and of injector hole angle, it was possible to sustain a wide variety of flame types, ranging from axial Type I flames, with little primary recirculation, to Type II and Type III flames with increasing intensity of primary recirculation.

The gas injector utilized allowed poorly mixed turbulent diffusion flames (Type I) to be supported when gas flowed through an axial port, but also supported more intensely mixed compact turbulent diffusion flames (Type II) when the gas flowed through radial ports at the same velocity. The oil injector used for doped distillate oil was water cooled and utilized standard pressure atomizing Monarch nozzles rated at 0.5 gph at 100 p.s.i. Most tests were conducted with 30°R solid cone nozzle. Additives could be bled into the fuel stream (gas and oil), or into the air stream without changing total flow rate. Further details can be found elsewhere.[10] The sampling and analytical system provided continuous monitoring of NO, NO_x, CO, CO_2, O_2 and SO_2 and has been described elsewhere.[9]

Results

Fig. 5 shows results of SO_2 addition to gaseous flames in which the fuel had been doped with NH_3. The flame was supported on the axial injector, yielding a Type I flame. Secondary air preheat temperatures was 496°K. The lowest curve shows baseline data for the doped fuel. SO_2 was added first in the fuel stream then in the secondary air. For the former case 40% enhancement of NO emissions was observed; in the latter, a much smaller effect was observed. This indicates the importance of local fuel rich regimes.

Results for doped distillate oil burner under slowly

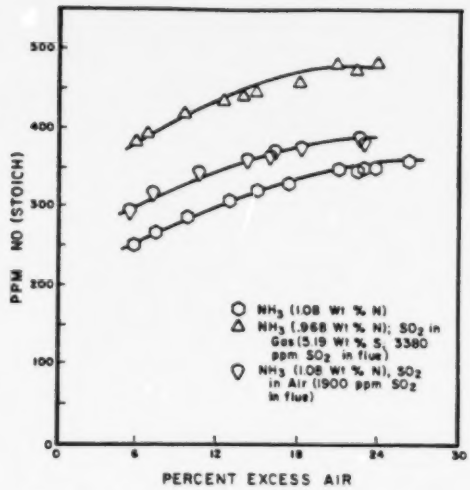

PPM NO (STOICH)
PERCENT EXCESS AIR
NH3 (1.08 Wt % N)
NH3 (.968 Wt % N); SO2 in Gas (5.19 Wt % S, 3380 ppm SO2 in flue)
NH3 (1.08 Wt % N), SO2 in Air (1900 ppm SO2 in flue)

FIG 5. Turbulent Diffusion Flame: Doped Natural Gas/Axial Injector (Type I Flame, 494°K Secondary Air Preheat).

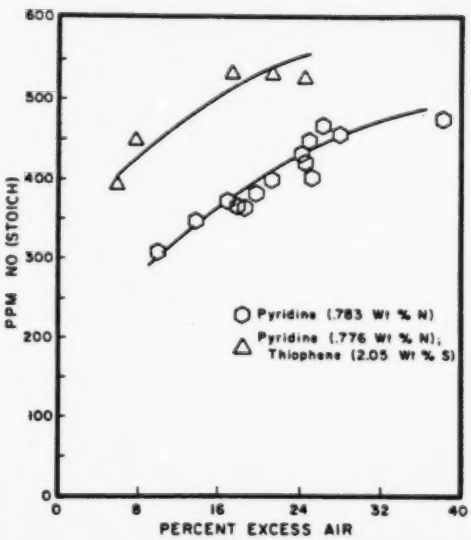


FIG 6. Turbulent Diffusion Flame: Doped Distillate Oil: Effect of Thiophene Addition on Fuel NO (30°R Nozzle, 427°K Secondary Air Preheat).

mixed conditions are similar (Fig 6). 2.05% wt sulfur as thiophene added to oil containing 0.78% wt nitrogen as pyridine increased NO emissions by 40%. In these experiments care was taken to ensure that the observed effects of fuel NO were due to

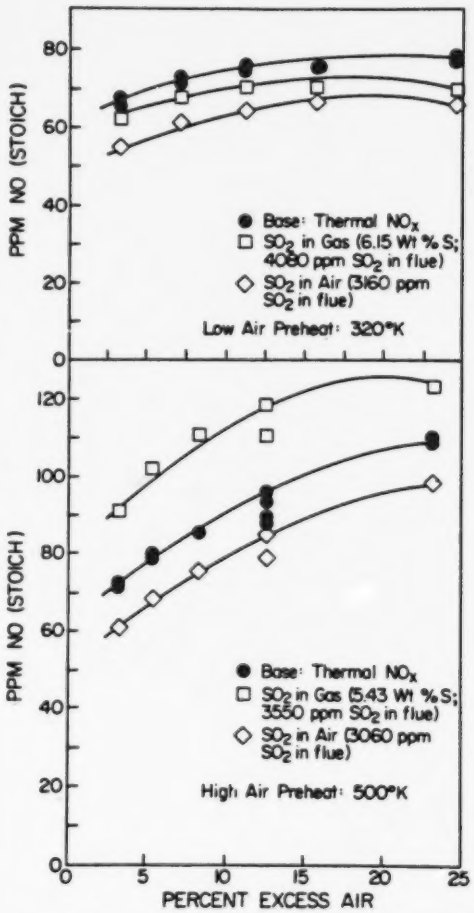
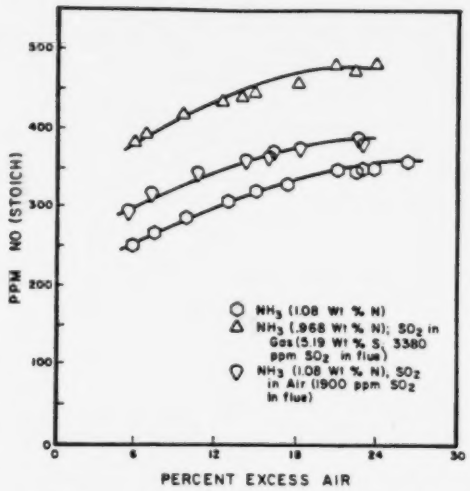

PPM NO (STOICH)
PERCENT EXCESS AIR
Base: Thermal NOx
SO2 in Gas (6.15 Wt % S; 4080 ppm SO2 in flue)
SO2 in Air (3160 ppm SO2 in flue)
Low Air Preheat: 320°K
Base: Thermal NOx
SO2 in Gas (5.43 Wt % S; 3550 ppm SO2 in flue)
SO2 in Air (3060 ppm SO2 in flue)
High Air Preheat: 500°K

FIG 7. Turbulent Diffusion Flame: Natural Gas/Axial Injector. Effect of SO_x on Thermal NO_x. Type I Flame.

the presence of fuel sulfur, and not to other transients introduced by the addition of thiophene. First it was shown that addition of benzene to a pyridine doped distillate oil did not, by itself, affect fuel NO emissions by changing evaporation characteristics. Thiophene is itself a fuel and accompanying changes in the stoichiometric air requirements due to its introduction into the pyridine-oil fuel mixture, have been considered in plotting the data.

It should be noted moreover that under well mixed (high swirl) conditions, addition of Thiophene had negligible effect on Fuel NO, probably becuase of the lack of importance of local fuel rich regions.

The role of SO_x addition on Thermal NO from Type I natural gas flames (axial injector) is shown


PPM NO (STOICH)
PERCENT EXCESS AIR
NH3 (1.08 Wt % N)
NH3 (.968 Wt % N); SO2 in Gas (5.19 Wt % S, 3380 ppm SO2 in flue)
NH3 (1.08 Wt % N), SO2 in Air (1900 ppm SO2 in flue)

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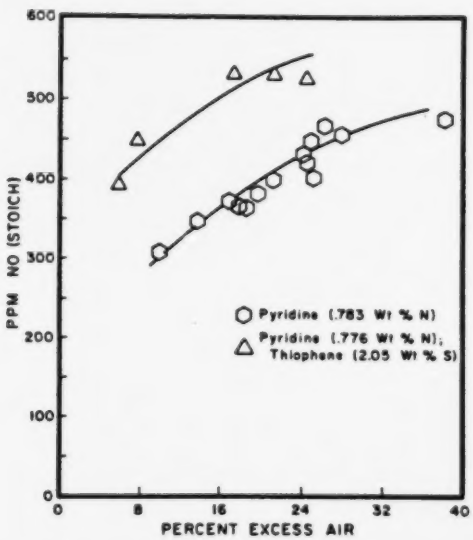

FIG 6. Turbulent Diffusion Flame: Doped Distillate Oil: Effect of Thiophene Addition on Fuel NO (30°R Nozzle, 427°K Secondary Air Preheat).

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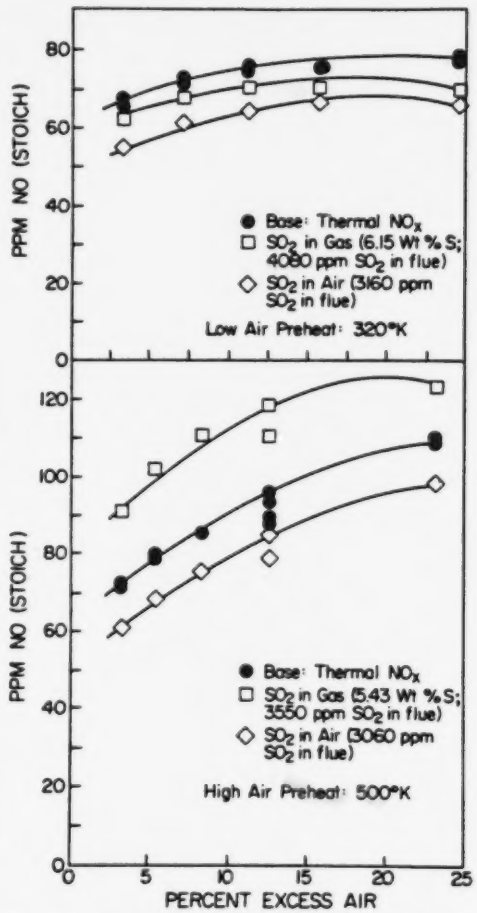
PPM NO (STOICH)
PERCENT EXCESS AIR
Base: Thermal NOx
SO2 in Gas (6.15 Wt % S; 4080 ppm SO2 in flue)
SO2 in Air (3160 ppm SO2 in flue)
Low Air Preheat: 320°K
Base: Thermal NOx
SO2 in Gas (5.43 Wt % S; 3550 ppm SO2 in flue)
SO2 in Air (3060 ppm SO2 in flue)
High Air Preheat: 500°K

FIG 7. Turbulent Diffusion Flame: Natural Gas/Axial Injector. Effect of SO_2 on Thermal NO_x. Type I Flame.

the presence of fuel sulfur, and not to other transients introduced by the addition of thiophene. First it was shown that addition of benzene to a pyridine doped distillate oil did not, by itself, affect fuel NO emissions by changing evaporation characteristics. Thiophene is itself a fuel and accompanying changes in the stoichiometric air requirements due to its introduction into the pyridine-oil fuel mixture, have been considered in plotting the data.

It should be noted moreover that under well mixed (high swirl) conditions, addition of Thiophene had negligible effect on Fuel NO, probably becuase of the lack of importance of local fuel rich regions.

The role of SO_2 addition on Thermal NO from Type I natural gas flames (axial injector) is shown

on Fig. 7. At low air preheat temperatures only inhibition was observed, while at high air preheat temperatures, a significant enhancement occurs when the sulfur is introduced in the fuel. Similar experiments utilizing the radial injector to stabilize Type II flames showed only inhibition of Thermal NO by SO_2 regardless of air preheat and/or mode of SO_2 addition. Since enhancement can only occur for Fenimore "prompt" NO, these data indicate that this mechanism may be of significant importance in Type I flames, even though the overall stoichiometry is fuel lean.

Discussion

The data from turbulent diffusion flames are consistent with those from the premixed flat flames if it is assumed that in the former, local fuel rich environments dominate as far as Fuel NO_x and prompt (Thermal) NO_x are concerned. Therefore Type I turbulent diffusion flames showed pronounced enhancement, while Type II flames did not. Increased temperatures promote the enhancement of Fenimore "prompt" NO by SO_2.

Clearly NO_x/SO_x interactions can be of first order in many practical turbulent diffusion flames, and fuel sulfur can cause a significant increase in fuel nitrogen conversion.

Mechanisms involving interactions of SO_x and NO_x are quite complex. Previous work has indicated that the route to NO from fuel nitrogen occurs through HCN, NCO and NH_x. Under fuel rich conditions, SO_2 is reduced to SO, H_2S and SH, and these species may well interact with NH_x to change the distribution among NH, NH_2 species. There exists evidence [11,12] that NH_3 or its derivatives, will reduce NO at moderately low temperatures. Note that at very low stoichiometric ratios, the equilibrium NH_3 concentration is greater than the equilibrium NH_3 concentration is greater than the equilibrium NO. It might be conjectured, therefore, that reduced sulfur species directly change the NH_x profiles in a flame, so that the NH_x species responsible for NO reduction persists far beyond the flame zone, thus, accounting for the steady NO reduction. This conjecture might also explain why the early NO peaks in the flat flame are so high. In the flame zone, the sulfur has delayed the formation of the NO reducing species until the post flame region is reached. Alternatively, the influence of sulfur may arise through direct interaction with the N atom [14]

$$N + SO \rightarrow NO + S$$

leading to high early NO levels followed by reduction either by NH_x or by N.

That the presence of sulfur allows NO profiles to decay sometimes below the baseline case is not surprising, since equilibrium NO values at $\Phi = 1.63$ are well below 1 ppm. In fact, given that sulfur promotes this slow decay, it is not surprising that it can allow measured values to be above or below the baseline values. It is hard to rationalize that the slow NO reduction observed results from reactions with CH [13] or other hydrocarbon fragments, since one would not expect them to persist so far from the reaction zone.

Our flat flame results differ from those of De Soete [8] in that he did not observe NO reduction prompted by sulfur, although he did observe significant enhancement of NH_3 conversion due to the presence of H_2S. However, measurements made in this work were over much longer residence times, and they involved both higher nitrogen and sulfur levels, and lower flame temperatures. Furthermore, De Soete's experiments on the role of sulfur utilized NH_3 and NO as nitrogeneous additives, while this work utilized C_2N_2. The nitrogen species involved may be important when sulfur is present.

It is interesting to note that the NO profiles measured here in the presence of sulfur, are qualitatively similar to NO profiles in fuel rich pulverized coal combustion [15] while the profiles without sulfur are not. The presence of sulfur in coal may have a significant effect on NO abatement by staged combustion, since one would expect sulfur levels in the volatiles to be high.

Acknowledgements

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COMMENTS

P. C. Malte, Washington State University, USA. Your measurements of the influence of sulfur on fuel-NO_x are very interesting, and indicate future research areas. The fact that you observe similar behaviour with both SO_2 and H_2S additives is consistent with measurements conducted elsewhere on sulphur doped flames. In a jet-stirred reactor fired on propane/air, Kramlich and Malte at Washington State University have found similar yields of sulphur products (SO_2, H_2S, COS, and CS_2), independent of the type of sulphur additive, to a first approximation. The additives were SO_2, H_2S and thiophene.

Your comments on possible kinetic pathways between the sulphur and nitrogen systems would be of interest here. One would think that the SO radical could play a role by interacting with the fuel-N conversion mechanism.

Authors' Reply. As discussed in the paper, there are a number of possible kinetic pathways that might explain the phenomena uncovered in this work. We think the SO radical, or the S atom may well play a role possibly through reactions such as

$$N + SO \rightarrow NO + S$$

which has been studied by Jacob and Winkler.[1] The interaction between fuel sulfur and fuel nitrogen oxidation mechanisms is most likely an indirect interaction. Measurements of intermediate nitrogenous and sulfur species are necessary to shed new light on this.

REFERENCE

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D. J. Seery, United Technologies Research Center, USA. Your data indicate that the flame temperature is rapidly decreasing in the region of the flame, where the NO concentration is measured. It may be therefore possible to interpret the NO decay as a reflection of this temperature decrease, which causes a shift in some partially equilibrated NO_x—SO_x reaction system.

Authors' Reply. Our data (Fig. 1) show that, in the presence of sulfur, NO is being reduced after flame temperatures have fallen below 1600°K. A shifting partial equilibrium may well play a rôle in determining the NO decay.

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K. Schofield, University of California, Santa Barbara, USA. As presented elsewhere at this symposiym M. Steinberg and I have been looking at sulfur chemistry in flames using laser fluorescence techniques to monitor directly and quantitatively for

the first time all the important sulfur species.

Firstly, SO_2 and H_2S additions are indistinguishable sources of sulfur in the absence of NO_x, which fact should be reflected in your data. We find that the chemistry of sulfur in stoichiometric and fuel rich $H_2/O_2/N_2$ flames is controlled completely by the extent to which radicals exceed their equilibrium concentrations. The relative ratios of sulfur species adjusts as the H and OH concentrations decay towards their thermochemical equilibrium values. I might suggest that in your work one possible explanation may lie not in direct NO_x/SO_x mechanisms, which may or may not be occurring to some extent, but possibly from the known catalytic effect of SO_x in facilitating a faster recombination mechanism whereby the excess radical concentrations are much reduced. This would be supported by the fact that you note the largest effects in more fuel-rich flames, which are known to depart increasingly from equilibrium.

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A. Fontijn, Aerochem Research Labs., USA. It is being suggested by discussors as (kinetically) hard to understand how SO_x can influence NO_x. However this problem has recently been discussed extensively by Glassman in his combustion text,[1] to which I refer both discussors and the authors as a starting point for interpretation. Dr. Schofield mentioned some flow tube experiments on the basis of which he finds it hard to believe your results. Presumably these are room temperature measurements; do they have much relevance to the present work?

REFERENCE

1. Glassman, I.: *Combustion*, Academic Press, New York, 1977.

Authors' Reply. Our data indicate that SO_2 and H_2S addition have similar qualitative effects on fuel NO, but different quantitative effects. In our experiments addition of H_2S had a smaller effect than addition of the equivalent amount of SO_2. However, under the very fuel-rich conditions examined here, H_2S addition will change the equivalence ratio slightly, and under these conditions, fuel NO is very sensitive to changes in equivalence ratio.

Sulfur does act as a free radical recombination catalyst.[1)] This effect has been shown[2)] to inhibit *Thermal NO* which has been formed through the Zeldovich reactions. We would not expect a decrease of O, and OH free radical concentrations to lead to a great *increase* in *fuel NO* in the early flame followed by a very slow decay of fuel NO at relatively low temperatures far (50–100 ms) from the flame front.

However, as discussed in the previous comments, we would all agree that the effect is probably due to some indirect interaction between fuel sulfur and fuel nitrogen oxidation mechanisms.

REFERENCES

1) Glassman, I.: *Combustion*, p. 230 ff, Academic Press, New York, 1977.
2) Wendt, J. O. L. and J. M. Ekmann: *Combustion Flame* 25, 355 (1975).

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